DRA

PRODUCTION AND DELIVERY OF VIOLET SOLAR CELLS

Contract NAS 8-29872

FINAL REPORT

Prepared for

MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama 35812

Prepared by

CENTRALAB SEMICONDUCTOR
GLOBE UNION INC.
El Monte, California 91734

(NASA-CR-144250) PRODUCTION AND DELIVERY OF VIOLET SOLAR CELLS Final Report (Globe-Union, Inc.) 37 p HC $4.00 CSCL 10A

N76-22661

Unclas
G3/44 15215

TABLE OF CONTENTS

PRODUCTION AND DELIVERY OF VIOLET SOLAR CELLS

1.0 INTRODUCTION

This program was planned for the fabrication and delivery of 300 "violet" solar cells, nominally 2 x 4 cm size, with covers attached, and of minimum conversion efficiency of 13% AMO.

In the course of this program, cells were delivered which met the target, and the experience gained in this period has been used to assess the probable performance for large scale manufacture of such cells. This program was the first one in which violet cells of good output were made with 2 x 4 cm slices.

2.0 TECHNICAL SECTION

2.1 Overall Violet Cell Requirements

This program was performed as part of the expansion phase of conventional violet cells from laboratory numbers to pilot line numbers. Thus, some of the problems encountered were those arising from transfer and expansion of a laboratory process. To appreciate these problems, the basic properties of a violet cell are discussed. The close interaction of all the process steps is emphasized, meaning that much tighter control of all steps is needed than for conventional cells.

2.2 Violet Cell Description

Violet cells are characterized by:

a. A very shallow (o.1 μm), highly doped N+ layer diffused into good cell quality P-silicon; the P-silicon has resistivity around 2 ohm-cm, giving good balance between high initial output, and good end-of-life output after particle radiation. This shallow PN junction allows increased short wavelength response; also, close control of the starting silicon properties, and of the diffusion conditions can provide a good quality PN junction (leading to high open circuit voltage, V_{OC}, and high curve fill factor, CFF) with good bulk perfection of

the P-silicon (thus maintaining high long wavelength response).

b. A contact metal structure which can preserve the good qualities of the PN junction. This implies that the contact metals do not form an opposing voltage barrier at the back contact (to the P-silicon) and also do not lead to penetration of the shallow PN junction, with decrease of V_{OC} and of CFF.

c. A front contact grid configuration which can reduce the cell series resistance, even though the N+ layer has very high sheet resistance (typically 100 to 500 ohm/sq.). This grid configuration consists of many (10 to 30 lines per cm) fine metal lines distributed across the N+ surface. The present photoresist methods used to form these fine line patterns are also capable of reducing the line width and the total covered area to allow increased active area compared to conventional cells.

d. An anti-reflective coating which maintains the additional short wavelength response provided by (a) above. In practice, suitable coatings have been Ta_2O_5 or Nb_2O_5, which have good short wavelength transmission, and also have relatively high refractive indices (2.1 - 2.25).

The high indices mean that the coated cells are not as well-matched to the interface with air, as they are to an interface with a dielectric cover (glass, quartz, etc.). This in turn means that a cover must be applied to a violet cell to obtain maximum output; this is also the condition existing when cells are flown in space.

One other condition is necessary to maintain the high violet cell response; the cover used must not have an ultraviolet rejection filter which severly restricts the transmission of short wavelength light. In practice, a cut-on wavelength of 0.35 μm (obtained by multi-layer coatings or from the natural cut-on for CeO_2-doped glasses) is satisfactory.

2.3 Violet Cell Process Steps

The main process steps are as shown in Figure 1.

Notes on the Steps

1. Select P-type silicon which is capable of making conventional cells of good bulk response. The resistivity range is 1 to 3 ohm-cm; and the silicon slice thickness is around 10 mils. One surface of the slice is carefully polished, to reduce work damage at this surface.
2. Perform a shallow N+ diffusion, to date, using a phosphorous system. The temperature rance used is 790 to 875^{o}C, and the corresponding diffusion times are 30 to 5 minutes.

The diffused layer is approximately 0.1 to 0.2 μm thick, and the sheet resistance of the layer exceeds 150 ohm-cm. The diffusion control must also reduce lattice strains, to ensure that the N+ layer, the PN junction, and the bulk P-silicon all have good cell quality.

3. Apply front contacts, in a fine grid pattern. This pattern can be defined by a shadow mask during evaporation or by use of optical masks and photoresist layers.
4. Apply a back contact by thermal evaporation.
5. Build up contact thickness by additional evaporation or electroplating.
6. Clean the PN junction by masking both large faces of the cell and using a combination of etchants to remove metal and disordered silicon around the slice edges.
7. Apply antireflective coating; generally of Ta_2O_5 or Nb_2O_5.
8. Test I-V characteristics under AM0 illumination.

Additional processes are involved including careful cleaning and surface preparation, etching, heat treatment to increase contact and coating adhesion, or coating properties. Sometimes a P+ layer is incorporated at the back surface by alloy-diffusion of an evaporated aluminum layer.

2.4 Interactions Between Process Steps

Several possible interactions can be seen:

a. If the silicon does not have good carrier perfection (as shown by estimating the carrier diffusion length) the bulk collection and therefore the long wavelength response will be low.

b. If the silicon surface is not damage-free, the shallow PN junction will not have adequate perfection for highest cell output.

c. The heat treatments used to increase adhesion may increase the tendency for impurities to penetrate the shallow N+ layer.

d. The various masking materials, especially the photoresist, if not removed completely, can lead to reduced adhesion of contacts or coatings.

e. The surface handling during cell processing must be minimized.

2.5 Experimental Work

Transfer, Consolidation, and Expansion of Laboratory Processes

Some of the initial 2 x 2 cm cells made fell below the goals (were around 70 mW, instead of 75 mW). The reasons were often subtle, involving slight changes in the trade-offs required to form the cells. It is convenient to discuss the fabrication problems separately under the headings below, even though

the overall results often depended strongly on the process interactions.

a. Silicon

The goal was to use crucible grown silicon, typical of that used on conventional cells. The violet cell processing, as expected, showed greater sensitivity than conventional cell processes to slight variations in silicon perfection; similar comments apply to slight variations in the surface preparation.

For 2 x 4 cm violet cells, two additional factors have to be considered. First, the larger slices, whether cut parallel to or across the growth axis, will have a wider variation in resistivity and other crystal properties than smaller slices. These differences could reduce cell output or could perhaps diminish the resistance to degradation by charged particle irradiation.

Also, some of the small but significant differences in silicon quality only became evident after close control of later process steps was achieved. For example, if the contact resistance is high (because of residual interface layers or inadequate contact thickness), if the active area is low (because the grids are too wide) or the antireflective coating does not have low short

wavelength absorption, small variations in silicon properties cannot be detected. Later in this process development, sufficient pilot line control was achieved to evaluate possible fluctuations in the quality of silicon ingots grown and processed in a normal manufacturing environment. Similar comments apply to the detection of small changes in the quality of the surface preparation; the chemical-mechanical polishing method, when closely controlled, appears adequate.

b. Diffusion

The diffusion process is important in obtaining high short wavelength response, and good cell properties. Some problems were encountered in attempting to increase the frequency of diffusion runs; build up of phosphorous layers on the quartz tube walls or on the diffusion boats increased the surface concentration, or increased the effective diffusion time. This resulted in reduced short wavelength response. This short wavelength response was also very sensitive to variations in the coating, either of thickness or of refractive index.

The methods used to evaluate the short wavelength response included cell measurement with:

(i) The use of the xenon lamp of the Centralab AMO

simulator.

(ii) The use of a filter, transmitting a narrow band around 0.4 μm, from an intense xenon lamp.

(iii) Spectral response measurements. For 2 x 2 cm cells, adequate output for (i) is 67 mA; some cells reached as high as 71 mA. For 2 x 4 cm cells, corresponding xenon lamp numbers were around 136 to 141.

The diffusion can also affect the bulk perfection of the silicon, leading to reduced long wavelength response. This parameter is checked by using only the tungsten lamp in the CRL simulator, or by spectral response measurements.

In addition to cell measurements, in-line monitoring of the diffusion process is achieved by measuring typical sheet resistance values for each run. The diffusion techniques have been adjusted to give best balance between high short wavelength response and good cell CFF. The former is achieved by high sheet resistance values; the latter is generally improved at low resistance values, which reduce the series resistance contribution of the diffused layer.

c. <u>Front Contact Application</u>

The range of sheet resistance values needed for high short wavelength response demand a line density in excess of 10 per cm. To maintain suitably fine lines, to reduce the inactive area while maintaining adequate distribution, requires a process capable of fine resolution in line formation. Mostly, fine line optical masks are used in combination with photoresists, to form the grid line pattern.

Some trade-off is required, because the photoresist method is best when combined with thin metal layers; to obtain adequate conductance, these metal layer thicknesses must be built up after fine line formation. An alternate method uses a fine line shadow mask and evaporated metal contacts. The practical problem is that at the line densities required, at least 2-3 times the line width is the finest line presently available from evaporation mask suppliers, even using their most advanced techniques. The line width results from the original line width on the mask, widened by any angling of the contact metals between the mask and the silicon. Several tests were run, to see if the sheet resistance range could be lowered (with reasonable maintenance of

short wave response), to allow lower line densities, and thereby increase the effectiveness of the available shadow masks.

The cell parameters most affected by this trade-off between high sheet resistance and fine grid lines are the short circuit current (I_{SC}) and CFF. The I_{SC} effects result from reduced active area; the CFF reduction from increased series resistance.

There is another problem with evaporation masks. To avoid the formation of an ohmic contact strip along one edge and to provide two pads with bars connecting the fine lines often requires the use of two separate masks, an unwanted complication.

Some of the work to achieve best balance of CFF and short wavelength response was impeded by a measurement fault. For cells like violet cells, which have two separate contact pads (four for 2 x 4 cm cells) rather than a continuous ohmic bar, and test fixture pickoff electrodes can have a voltage difference between the electrodes, and the electronic measurement circuitry can generate a corrective signal, providing an I-V curve with apparent high values of CFF. When the pickoff

electrodes were shorted externally (as they are by the ohmic bar), lower values were measured.

At present, some decrease from the highest short wavelength values possible is tolerated, to ensure high CFF. The short circuit current from the xenon light in the CRL simulator is typically 134-138 mA, rather than earlier values around 138-142 mA, but this leads to CFF values nearer 0.79 than 0.77 with a net gain in output. Also for highest output, the photoresist methods are presently preferred, to maintain high active area.

The photoresist process introduces another problem, that of contact peeling. The need for good line resolution, combined with the possibility of surface films remaining after photoresist removal, can sometimes give much peeling; to prevent N+ layer penetration, the heating cycles cannot be chosen to give highest contact adhesion. Improved process control has minimized this peeling, which masked many early attempts to optimize all the process steps. The contact adhesion has been proved to be satisfactory.

d. Back Contact Application

The application of the back contact is less demanding than for the front contacts, but is nevertheless very important to maintain low series resistance, and high CFF. In general, suitable back contacts have been obtained; some peeling problems occasionally occur either from residual films after photoresist processes or from the contact buildup. Even with a relatively rough surface, the back contact adhesion after parallel gap welding appears adequate.

e. Antireflective Coating

The control of the coating has proved to be most important for highest output violet cells. Several different application methods for Ta_2O_5 have been tried, including electron beam evaporation and sputtering. It is possible to form good layers in several ways, but not all Ta_2O_5 layers have adequate properties for good cells. For example, with some methods, the structural properties of the coating leads to a chance of refractive indices between 2.0 and 2.25, and possibly can cause additional absorption in the short wavelength region. Also, variation in the coating thickness control which must be precise, can lead to reduced I_{sc}. The lower refractive

index can reduce gain observed when the cell has a transparent cover applied to it. Any thin surface layers, organic or cleaning solution residues, left during processing, can interact with the thin Ta_2O_5 layer, which is ~550 Å thick, and these layers usually reduce the effectiveness of the antireflecting coatings.

To obtain highest Ta_2O_5 properties, a reasonably severe heat cycle is required ($\simeq 500^oC$). This temperature range can lead to undesired changes in the contact barriers, increasing the series resistance of the cell, or to some penetration of the shallow N+ layer, with the possibility of reduced V_{oc} and/or reduced CFF.

f. <u>Summary of Consolidation of Conventional Violet Cell Processes</u>

In the early part of this contract, 2 x 2 cm violet cells around 68-70 mW were being made; with increased understanding and control of the processes, cells in the range 70-72 mW, with good violet response, were obtained. Lately, further advances in control of active area, of diffusion and coating, and silicon surface treatment have given 2 x 2 cm cells in the range 71-75 mW; for 2 x 4 cm cells, values around

140-150 mW have been obtained. Present indications are that the higher values can be achieved by combination of the closely controlled processes listed above and by restriction to carefully screened silicon; not all normal ingots have yielded the highest output cells, probably because of slightly reduced carrier diffusion length, caused by impurities or structural defects.

3.0 RESULTS OBTAINED ON PROGRAM

3.1 Cell Fabrication

The improved understanding of the violet cell problems, using larger numbers fabricated per day, was extended to make 2 x 4 cm violet cells. Three hundred (300) typical state-of-the-art cells were delivered.

3.2 Cell Measurements

3.2.1 I-V Characteristics

The design of the front contacts led to the use of four pickoff pads (each ~ 2 mm x 1 mm) spaced 1 cm apart along one 4 cm edge of the cell.

During the contract, some difficulties were encountered in measuring cells with such pads. These difficulties were traced to the separation of the current and voltage pickoff contacts on the pads; if any potential drop existed between contact pads, the read-out circuitry would generate a corrective signal, which led to an I-V curve which was "squarer" (higher CFF) than the real case.

3.2.2 Simulator Calibration

All the cell parameters given in this report are based on readings under the Centralab AMO simulator, calibrated using a conventional cell which had been balloon-flight tested. These readings agreed well with other measurements on the same cells as expected because the other simulators were also calibrated with a conventional balloon-flight cell. Table 1 summarized some correlation tests run early in the probram.

During the course of this program, some conventional violet cells were flown on a balloon by JPL. Some tests using the CRL simulator calibrated by these violet cells showed that 2 x 2 cm violet cells read 3-5 mA higher under the new setting. These tests suggest that probably all the I_{sc} values quoted in this report could justifiably be increased by 6-10 mA. Recently there has been more emphasis on evaluating high efficiency cells under AMO simulators calibrated with a balloon-flown violet cell.

Also, other simulators (e.g., pulsed xenon types) have often been used to characterize high output

cells; often these simulators are rich in short wavelength output, which gives additional current for violet cells. The in-orbit results from Timiation III* showed that cells generally measured higher in early orbits (before significantly irradiation) than in ground tests. This suggests that considerably increased care will be needed to accurately characterize high output cells like those produced on this contract.

3.2.3 Short Wavelength Output

The prime requirement for violet cells is enhanced output in the short wavelength region (below 0.5 μm). Early tests combined evaluation using the xenon lamp in the CRL simulator, measurement of the cell output under a xenon lamp passed through a narrow band filter, centered on 0.4 μm, and some spectral response measurements. Good correlation was obtained between the simulator and filtered xenon illumination; therefore later work used only the simulator xenon output as a check that adequate short wavelength output was maintained.

* R.L. Statler, F.C. Treble, "Solar Cell Experiments on the Timation III Satellite," p. 369, Proceedings of International Conference on Photovoltaic Power Generation, Hamburg, 1974.

3.2.4 Spectral Response Measurements

An attempt was made to obtain absolute spectral response data for typical 2 x 2 cm violet cells, with and without a cover. Although the task was subcontracted to a group recommended by the National Bureau of Standards, it was found that the results submitted to CRL were not more reliable than CRL in-house measurement of absolute spectral response. Typical response curves for a conventional and a violet cell are given in Figure 2.

3.2.5 Cover Gains

A good check on the reproducibility of both the AR coating and the cell spectral response can be obtained by measurement of the cell output with and without a cover applied.

Table 2 summarizes such measurements.

3.3 Cells Shipped

Four shipments were made, as follows:

(a) Five typical 2 x 4 cm, CeO_2-glass covered cells for preliminary evaluation;

(b) Twenty-one 2 x 4 cm, CeO_2-glass covered cells, typical of earlier work;

(c) One hundred and thirty 2 x 4 cm cells with CeO_2 glass covers, with typical I-V parameters as given below. (The covers used were CeO_2-doped glass, 6 mils thick.)

<u>Typical I-V parameters</u> (AM0, cells at 28°C)

I_{sc} range	306-323 mA
V_{oc} range	581-592 mV
I_{475} range	290-303 mA
CFF range	.74-.78

For these cells, generally the maximum power followed the CFF values. The I-V values are given in Table 3.

(d) One hundred and fifty 2 x 4 cm cells, with fused silica covers, 0.35 um cut-on. The I-V parameters were similar to those in (c), with somewhat higher CFF and lower I_{sc}. I-V values are given in Table 4.

3.4 Environmental Tests on Cells

Early fabrication problems (particularly in peeling of contacts) delayed full environmental evaluation. However, some tests have been completed on the present cell design, and the results are summarized here.

(a) <u>Humidity Tests</u>

After 30 days at 45°C, 95% relative humidity, violet cell showed very small changes in output, with performance comparable to those observed on Ti-Pd-Ag contacts.

(b) Welding Tests

For parallel-gap welding of silver-coated molybdenum tabs to the silver contacts, fair pull strength was obtained.

for 45° pull tests, the following pull forces were:

Front contacts: 100-200 gm.

Back contacts: 100-250 gm.

Also, most of the pull failure-modes were "weld-failure." There was no significant change in I-V characteristics observed using these weld cycles; this suggests that some possibility remains to increase the severity of the weld cycle, if slightly higher pull-strengths are considered necessary.

(c) Temperature Cycle Tests

Some of those cells with welded tabs attached were subjected to 16 temperature cycles from $-180^{\circ}C$ to $+60^{\circ}C$, with dwell times around 5 minutes, and temperature changed $\sim 10^{\circ}C/min.$; no significant change in I-V characteristics was measured for any of the cells.

(d) Coating Tests

Use of the conventional coating test (exposure to steam for 10 minutes plus twenty eraser strokes, did

not produce any significant deterioration in the Ta_2O_5 coating.

3.5 Wraparound Contact Cells

Several different methods and fabrication sequences were tried to apply wraparound contacts to the very shallow junction diffused slices. To date, the results have been very disappointing.

The main problem is in wrapping the very shallow junction around one edge and providing good ohmic contacts on this edge, without severe reduction in CFF. Attempts to use thin insulating layers usually led to reduced contact adhesion (often paling easily).

Much more work is needed before any realistic evaluation can be made of the probability of fabricating such cells on a larger scale.

4.0 CONCLUSIONS AND COMMENTS

The main objectives of the contract were realized. The violet cell process was expanded to a pilot scale and was extended to form good quality violet cells, 2 x 4 cm in size. It was possible to maintain good short wavelength output with high CFF; the coating was good and gave good output when a cover was applied. The contacts gave the most problems, in control of active area, to reduce series resistance, and in physical problems, such as peeling, or reduced weldability.

The main problems in further scaling-up are now appreciated. First, a much higher level of control of <u>all</u> cell parameters (including specification and preparation of the silicon and its surface preparation, diffusion, front and back contacts and coating). In addition, the cleaning between separate steps must also be closely controlled. However, even with this need for additional care, it is considered that basically the violet cell can be extended to large scale production. The major decision to be made is whether to scale up the photoresist method (photoresist application, suitable masks, pattern development, contact application, and cleaning of the surfaces) used presently to form the find grid pattern, or to rely on evaporation shadow masks, with the chance

that slightly reduced (3-5%) active area will be available on the cells. With present technology, the photoresist method is preferred. The other process steps appear capable of economic expansion.

One consequence of the closer control required to keep the cell output high is that the chance of setting standardized cell specifications is higher than for conventional cells. To avoid dual specification, this standardization should apply to cells with acceptable covers applied. Other standardization features may include the mechanical size of the slice. No detailed electrical specification need be given for the contacts because the process must be adjusted to ensure the high output; some contact specification will be needed for array weldability or solderability. Similar comments apply to the coating specification; if the cell is to have high output, and good short wavelength output with a cover applied, the coating need not be specified separately in great detail; again the process control to give high output cells will ensure close control of the coating properties.

Because the cells will probably be covered and since the interconnection methods do not appear to be highly specialized, the choice of the interface between cell and array

manufacture can be flexible and can be chosen to ensure best overall performance and economy. As far as radiation resistance specification is concerned, the same general comments apply as to diffusion or coatings, namely, that while maintaining high violet cell output, at the same time, the radiation resistance will be controlled at least as closely as that for conventional cells. The main controlling factor is the silicon resistivity; the added output for the violet cell (active area, higher CFF, higher short wavelength response) is essentially radiation resistant.

At the present stage of development, it does not appear possible to specify wraparound contacts for violet cells; if array designs will be considerably improved with these contact structures, more work is needed to evolve a suitable production process.

5.0 RECOMMENDATIONS

The work in this program has provided three hundred (300) typical 2 x 4 cm violet cells for detailed evaluation. After such evaluation, it is recommended that the sponsor group and the cell manufacturer meet to identify the present technology and to discuss the priorities in further scaling-up. In particular, suggestions should be made on how much of the array formation should be performed by the cell fabrication processes.

TABLE 1

Correlation Tests of I-V Characteristics

Test Conditions

(A) CRL - Standard Simulator calibration
(B) - Standard " "
(C) JPL - " " "
(D) COMSAT Simulator calibration, modified for Violet Cell

Cell No.	Test Conditions	Cell Temp. ^{o}C	I_{sc} mA	P Max mW	V_{oc} mV
353-8*	A	28	156.5	72	587
	C	28	157.4	71.7	590
353-2*	A	28	158.5	72.5	585
	C	28	159.5	72.2	591
350-1*	A	28	165.7	74.5	591
	C	28	165.7	73.6	592
4+	B	25	154	62	595
	D	25	155.3	60	595
19*	B	25	163.8	75	600
	D	25	163.5	76	603

* Covered
\+ Uncovered

TABLE 2

Cover Gains

Cover	Typical I_{sc} Gain* (mA)	% Gain	Main Losses
CFQ	8	5	--
CFQ + 0.35 μm	6.5	4+	Long λ
CFQ + 0.4 μm	4	2.5	Short λ
0211	6.5	4+	--
0211 + 0.4 μm	4	2.5	Short λ
CeO_2 glass	8	5	--
Teflon	7.5	4.5+	--

* For 2 x 2 cm cells.

<u>TABLE 3</u>

I-V Characteristics, Partial Final Shipment
2 x 4 cm^2 Violet cells, plus CFS cover, 0.35 μm cut-on filter
Cell Temperature 28^oc

SHIPPING NO.	Voc (mV)	Isc (mA)	I_{475} (mA)	P_{475} (mW)
1	586	320.0	292.3	138.8
2	588	315.3	294.2	139.7
3	589	320.4	298.0	141.6
4	585	313.9	291.0	138.2
5	585	318.4	298.4	141.7
6	585	323.0	298.7	141.9
7	584	313.5	296.4	140.8
8	591	315.5	302.9	143.9
9	587	317.9	296.0	140.6
10	589	309.6	300.2	142.6
11	585	314.4	293.6	139.5
12	590	312.6	293.1	139.2
13	592	309.0	292.3	138.8
14	589	316.7	296.2	140.7
15	589	317.2	296.7	140.9
16	584	312.6	293.1	139.2
17	589	308.6	295.0	140.1
18	585	306.7	290.8	138.1
19	586	314.1	295.7	140.5
20	583	312.9	291.3	138.4
21	592	307.1	294.7	140.0
22	592	309.8	293.3	139.3
23	586	307.5	290.0	137.8
24	590	312.6	293.8	139.6
25	590	311.2	295.7	140.5
26	584	314.1	297.0	141.1
27	589	316.1	297.7	141.4
28	591	313.7	294.2	139.7
29	588	317.2	295.2	140.2
30	588	313.9	290.9	138.2
31	588	312.1	294.9	140.1
32	587	312.8	290.7	138.1
33	588	315.6	292.4	138.9
34	583	316.5	295.5	140.4
35	588	314.6	298.6	141.8
36	592	309.9	297.1	141.1
37	584	316.2	296.0	140.6
38	590	311.0	296.1	140.7
39	592	311.6	290.8	138.1
40	593	312.3	296.7	140.9

TABLE 3 (continued)

SHIPPING NO.	Voc (mV)	Isc (mA)	I_{475} (mA)	P_{475} (mW)
41	588	314.2	291.6	138.5
42	582	321.1	291.2	138.3
43	587	310.6	297.9	141.5
44	592	313.0	302.1	143.5
45	590	314.2	301.6	143.3
46	588	319.5	291.0	138.2
47	585	317.0	290.2	137.8
48	590	316.1	303.0	143.9
49	585	319.7	298.3	141.7
50	583	319.5	293.8	139.6
51	581	321.8	293.0	139.2
52	589	318.0	298.2	141.6
53	587	320.2	296.5	140.8
54	586	316.2	290.2	137.8
55	589	316.0	289.9	137.7
56	588	321.0	299.1	142.1
57	590	319.2	295.7	140.5
58			290.5	138.0
59			296.0	140.6
60	Not	Not	292.4	138.9
61			294.9	140.1
62	Recorded	Recorded	292.2	138.8
63			293.9	139.6
64			299.9	142.5
65			291.3	138.4
66			292.3	138.8
67			294.5	140.0
68			295.3	140.3
69			298.9	142.0
70			298.7	141.9
71			290.3	137.9
72			295.6	140.4
73			290.4	137.9
74			295.3	140.3
75			290.6	138.0
76			293.8	139.6
77			291.3	138.4
78			291.4	138.4
79			292.7	139.0
80			292.1	138.7
81			296.2	140.7
82			300.4	142.7
83			297.2	141.2
84			296.2	140.7
85			293.8	139.6

TABLE 3 (continued)

SHIPPING NO.	Voc (mV)	Isc (mA)	I_{475} (mA)	P_{475} (mW)
86	Not	Not	297.4	141.3
87	Recorded	Recorded	290.9	138.2
88			299.8	142.4
89			294.9	140.1
90			294.3	139.8
91			300.7	142.8
92			300.1	142.5
93			295.6	140.4
94			295.4	140.3
95			293.3	139.3
96			297.2	141.2
97			298.9	142.0
98			289.9	137.7
99			292.6	139.0
100			298.6	141.8
101			293.2	139.3
102			295.4	140.3
103			300.1	142.5
104			292.5	138.9
105			300.7	142.8
106			294.2	139.7
107			294.9	140.1
108			299.6	142.3
109			295.0	140.1
110			291.8	138.6
111			295.8	140.5
112			292.9	139.1
113			301.7	143.3
114			291.3	138.4
115			298.1	141.6
116			295.4	140.3
117			297.7	141.4
118			293.2	139.3
119			301.0	143.0
120			297.1	141.1
121			300.2	142.6
122			294.4	139.8
123			297.1	141.1
124			293.1	139.2
125			294.1	139.7
126			290.8	138.1
127			292.3	138.8
128			297.4	141.3
129			297.2	141.2
130			292.7	139.0
131			291.7	138.6
132			290.8	138.1
133			296.5	140.8
134			295.1	140.1

TABLE 4

I-V Characteristics, Remainder of Final Shipment.
2 x 4 cm^2 Violet Cells, 63 plus CFS cover, 0.35 μm cut-on filter, 87 uncovered.

Test Conditions Simulator set with B.F. Violet Cell, Cell Temp. 25°c

SHIPPING NO.	Voc (mV)	Isc (mA)	I_{475} (mA)	P_{475} (mW)
F-1	597	317.9	302.2	143.5
F-2	604	328.6	305.2	145.0
F-3	602	320.6	297.9	141.5
F-4	606	321.9	312.6	148.5
F-5	596	321.9	289.9	137.7
F-6	607	321.5	314.8	149.5
F-7	606	315.1	306.4	145.5
F-8	607	319.4	273.3	129.8
F-9	599	318.2	305.5	145.1
F-10	594	314.0	295.6	140.4
F-11	607	324.6	311.9	148.1
F-12	603	313.1	299.1	142.1
F-13	601	315.1	300.1	142.5
F-14	601	320.8	308.3	146.4
F-15	607	325.7	314.0	149.2
F-16	604	317.7	309.1	146.8
F-17	601	322.0	308.9	146.7
F-18	603	318.0	307.2	145.9
F-19	606	319.5	301.1	143.0
F-20	602	323.5	307.1	145.9
F-21	603	326.6	299.8	142.4
F-22	605	320.7	310.8	147.6
F-23	601	319.8	305.6	145.2
F-24	600	317.8	303.8	144.3
F-25	607	325.1	313.7	149.0
F-26	607	321.0	303.9	144.4
F-27	601	321.7	305.7	145.2
F-28	597	313.8	305.5	145.1
F-29	599	320.5	293.5	139.4
F-30	604	324.8	306.9	145.8
F-31	603	320.4	295.7	140.5
F-32	595	325.0	302.0	143.5
F-33	602	313.9	303.3	144.1
F-34	610	326.2	317.5	150.8
F-35	605	322.7	307.2	145.9
F-36	597	325.8	314.0	149.2
F-37	600	327.0	297.2	141.2
F-38	597	315.0	306.0	145.4
F-39	600	320.5	294.7	140.0
F-40	599	317.7	275.0	130.6

TABLE 4 (continued)

SHIPPING NO.	Voc (mV)	Isc (mA)	I_{475} (mA)	P_{475} (mW)
F-41	601	321.1	309.3	146.9
F-42	604	319.1	289.8	137.7
F-43	593	320.0	291.0	138.2
F-44	601	319.1	309.0	146.8
F-45	604	317.2	273.3	129.8
F-46	592	320.6	292.4	138.9
F-47	606	324.7	271.7	129.1
F-48	606	322.8	309.4	147.0
F-49	605	325.3	258.0	122.6
F-50	599	317.7	308.6	146.6
F-51	602	317.4	305.4	145.1
F-52	603	319.6	282.0	134.0
F-53	608	321.5	307.7	146.2
F-54	598	317.0	288.3	136.9
F-55	596	317.0	282.5	134.2
F-56	603	321.4	299.1	142.1
F-57	603	319.5	291.6	138.5
F-58	594	318.5	281.4	133.7
F-59	603	316.1	273.4	129.9
F-60	605	321.3	305.0	144.9
F-61	600	312.8	280.0	133.0
F-62	605	318.6	304.1	144.4
F-63	605	316.8	307.5	146.1
F-64	590	306.8	291.4	138.4
F-65	600	304.0	291.7	138.5
F-66	599	297.1	289.3	137.4
F-67	599	303.8	290.9	138.2
F-68	599	300.6	291.7	138.6
F-69	604	301.1	293.7	139.5
F-70	598	303.6	294.2	139.7
F-71	599	303.8	290.0	137.8
F-72	598	304.3	291.2	138.3
F-73	599	301.0	289.7	137.6
F-74	603	304.6	291.1	138.3
F-75	594	306.3	293.4	139.4
F-76	593	302.4	287.1	136.4
F-77	600	302.3	294.6	139.9
F-78	593	302.3	291.0	138.2
F-79	590	307.4	290.0	137.8
F-80	598	306.4	294.2	139.7
F-81	601	303.5	292.7	139.0
F-82	606	310.9	296.1	140.6
F-83	602	302.7	291.3	138.4
F-84	598	292.1	283.1	134.5
F-85	599	302.8	285.3	135.5

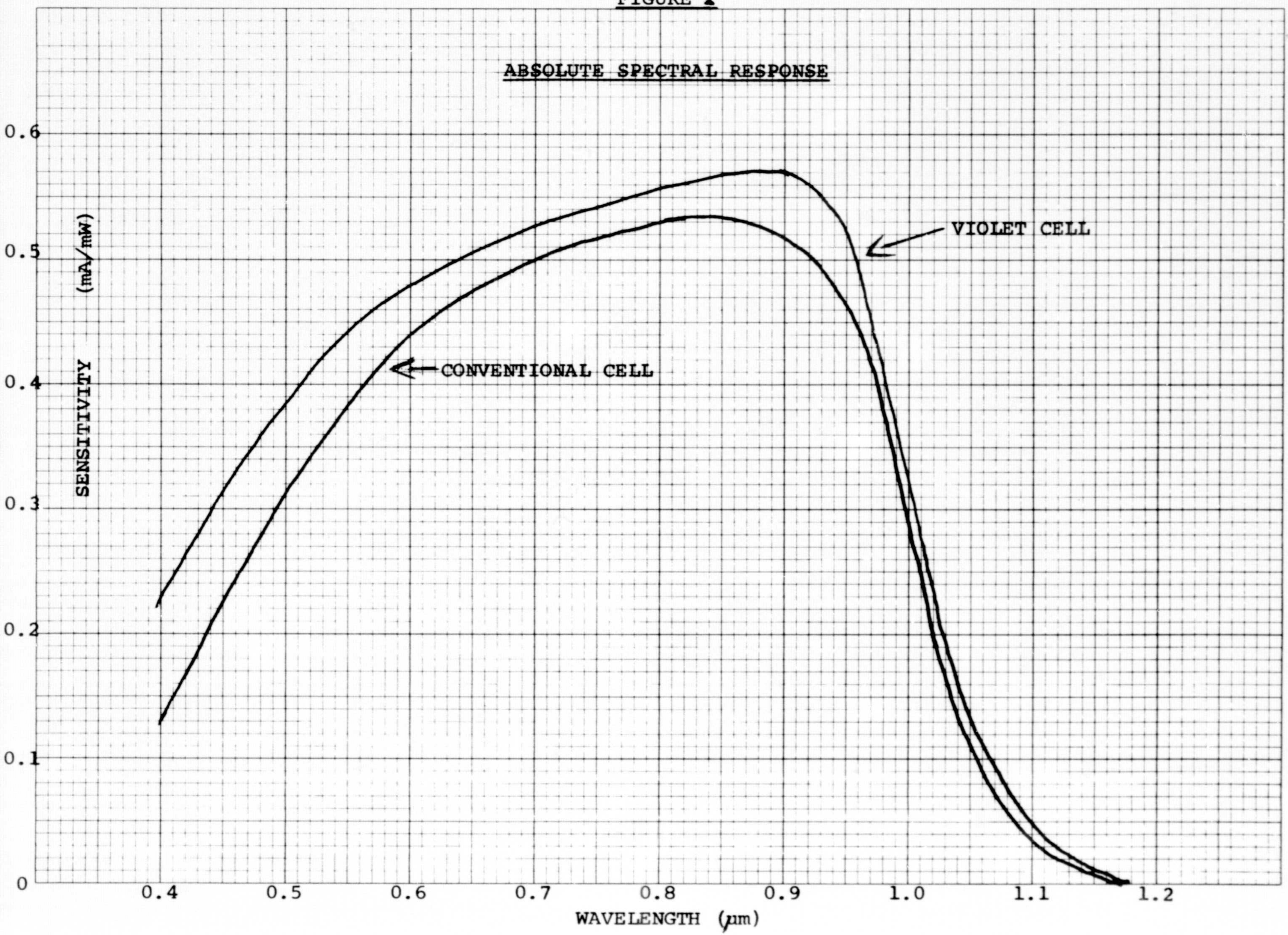
TABLE 4 (continued)

SHIPPING NO.	Voc (mV)	Isc (mA)	I_{475} (mA)	P_{475} (mW)
F-86	595	306.4	288.0	136.8
F-87	603	300.5	283.3	134.6
F-88	587	304.0	287.9	136.8
F-89	591	303.7	288.4	137.0
F-90	596	299.6	289.0	137.3
F-91	598	304.1	294.2	139.7
F-92	602	305.6	292.4	138.9
F-93	598	306.0	295.4	140.3
F-94	600	304.3	290.3	137.9
F-95	600	304.0	290.7	138.1
F-96	600	304.7	290.3	137.9
F-97	597	305.0	291.0	138.2
F-98	603	304.0	291.0	138.2
F-99	598	304.4	290.0	137.8
F-100	599	303.0	290.3	137.9
F-101	598	300.4	290.0	137.8
F-102	598	305.1	294.4	139.8
F-103	603	302.8	293.4	139.4
F-104	600	307.0	297.4	141.3
F-105	592	302.1	289.0	137.3
F-106	606	300.3	291.0	138.2
F-107	604	306.7	289.5	137.5
F-108	603	303.5	289.0	137.3
F-109	597	300.1	287.8	136.7
F-110	603	302.1	287.0	136.3
F-111	597	301.1	290.7	138.1
F-112	594	302.7	289.3	137.4
F-113	605	308.0	297.2	141.2
F-114	599	305.3	295.7	140.5
F-115	608	312.8	304.1	144.4
F-116	604	299.8	287.1	136.4
F-117	595	305.2	292.0	138.7
F-118	601	305.6	295.6	140.4
F-119	596	309.6	297.3	141.2
F-120	606	312.5	301.1	143.0
F-121	596	298.4	286.6	136.1
F-122	600	301.7	291.2	138.3
F-123	603	308.2	297.7	141.4
F-124	594	309.1	293.9	139.6
F-125	608	308.2	300.8	142.9
F-126	602	302.7	288.6	137.1
F-127	607	309.0	298.3	141.7
F-128	605	305.4	295.0	140.1
F-129	602	307.9	300.0	142.5
F-130	604	298.4	288.8	137.2

TABLE 4 (continued)

SHIPPING NO.	Voc (mV)	Isc (mA)	I_{475} (mA)	P475 (mW)
F-131	601	306.6	295.3	140.3
F-132	603	309.6	294.1	139.7
F-133	602	303.3	296.5	140.8
F-134	602	305.0	296.5	140.8
F-135	595	300.5	289.4	137.5
F-136	606	305.5	294.1	139.7
F-137	605	298.4	292.7	139.0
F-138	604	307.5	299.5	142.3
F-139	602	303.0	290.2	137.8
F-140	604	304.1	294.5	139.9
F-141	605	311.6	299.1	142.1
F-142	606	304.7	296.4	140.8
F-143	600	309.5	300.5	142.7
F-144	595	303.3	292.5	138.9
F-145	600	308.3	298.5	141.8
F-146	604	306.8	299.3	142.2
F-147	603	309.1	299.6	143.2
F-148	605	297.4	289.2	137.4
F-149	608	304.7	297.1	141.1
F-150	605	303.9	292.4	138.9

FIGURE 1


ABSOLUTE SPECTRAL RESPONSE
SENSITIVITY (mA/mW)
0.6
0.5
0.4
0.3
0.2
0.1
0
VIOLET CELL
CONVENTIONAL CELL
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
WAVELENGTH (μm)